LASER ION ABUNDANCE IN CAPILLARY DISCHARGES

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Abstract

Steady-state ionisation populations, average charge state and specific energy have been calculated using IONMIX code for atomic mixtures relevant to capillary discharge pumped X-ray lasers. Results for Argon, Sulphur, Polyethylene and Teflon under "coronal" equilibrium are presented. Dependencies of average charge state, electron temperature and resistivity on the specific energy have been evaluated.

1. Introduction

Fast capillary discharge is a simple promising way of table-top soft X-ray laser pumping. Recent experiments in several laboratories have demonstrated the amplified spontaneous emission at various XUV and soft x-ray wavelengths corresponding to quantum transitions of various hydrogen-like and neon-like ions [4-7]. Two pumping schemes have been used. Recombination scheme was successful with hydrogen-like ions and collisional one with neon-like ions. For a recombination pumped laser the plasma must be quickly ionised beyond charge state of interest and than rapidly cooled to achieved strong recombination into upper laser level. For collisionally pumped scheme the plasma needs to be heated to a particular charge state and than the proper (neon-like) ions have to be quickly pumped by over heated electrons. The quick heating accompanied by plasma compression may be achieved via z-pinch.

There are several features of the capillary discharge that are of particular interest as high aspect ratio (length/diam.) minimizing the trapping of transfer radiation, uniform longitudinal plasma profile and close proximity of the capillary wall supresing the instability in z-pinch plasma.

The close proximity of the wall may also be a drawback because it may change the initial composition of the ionised gas mixture through material ablation and it may increased the cooling of plasma through thermal conduction.

2. Theoretical Background

To estimate the required plasma parameters and to judge the influence of wall ablation in various pumping schemes we have calculated the ionisation fractions for different atomic mixtures using the IONMIX code [1]. This code computes the steady-state ionisation and excitation populations for a mixture of up to 10 different atomic species and also the thermodynamic properties of plasma such as the specific energy, average charge state, pressure and heat capacity.

The relative species, ionization and excitation fractions are defined as $f_k = \frac{n_k}{n_{tot}}$, $f_{jk} = \frac{n_{jk}}{n_k}$, $f_{ijk} = \frac{n_{ijk}}{n_{jk}}$, where n_k, n_{jk}, n_{ijk} refer the number density of nuclei of gas species k, then j-th ionization state of species k, and the i-th excitation state of the j-th ionization state of species k, and n_{tot} is total number density of nuclei. The average charge state is defined as $< Z >= \sum_k f_k \sum_{j=1}^{Z_k} f_{jk}\, j$, the specific energy is determined by

$$\varepsilon = n_{tot}[\frac{3}{2}(1+ < Z >)T + \sum_k f_k \sum_{j=1}^{Z_k} f_{jk}(\sum_{i=0}^{j-1} \Phi_{ik} + \sum_{i=n_0+1} f_{ijk}(\Delta\varepsilon_{in_0})_{jk})] \qquad (1)$$

where Φ_{ik} are the ionization potentials, and $\Delta\varepsilon_{in0}$ are the excitation energy differences. To estimate the electric plasma resistivity we have used the Spitzer formula [8] :

$$\eta = 3.04 \times 10^{-3} < Z > \ln\Lambda/(\gamma_e T_e^{3/2}) \qquad (2)$$

where $\gamma_e \in (0.58, 1)$ is the e-e collisions correction factor and Λ is Coulomb logarithm.

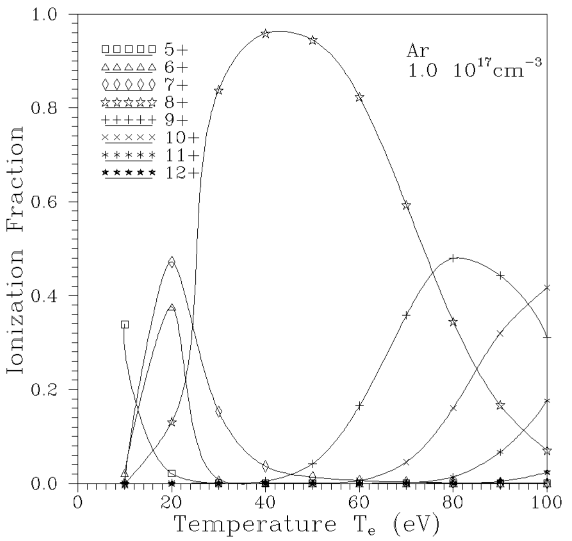

Fig. 1. Relative ionisation fractions of Argon ions.

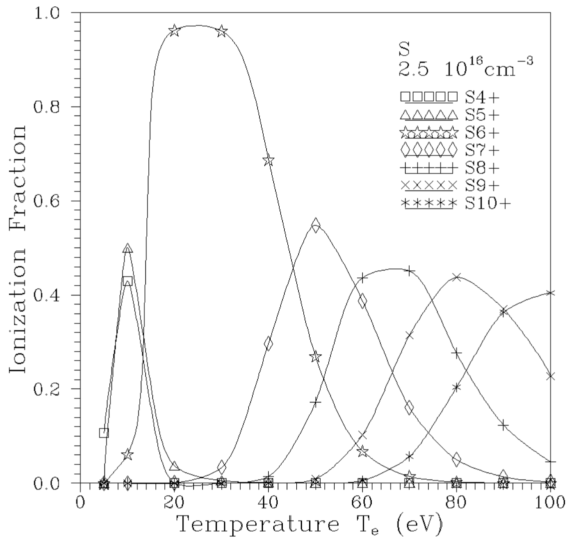

Fig. 3. Relative ionisation fractions of Sulphur ions.

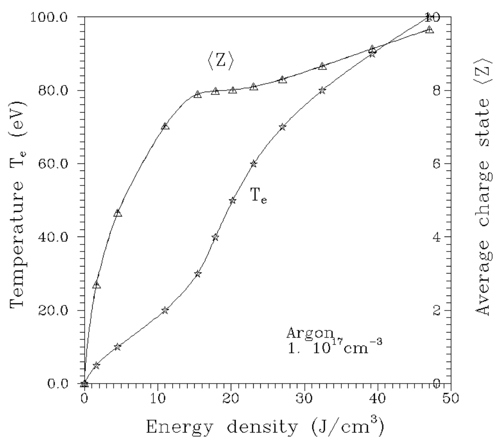

Fig. 2. Electron temperature and average charge dependencies. on specific energy

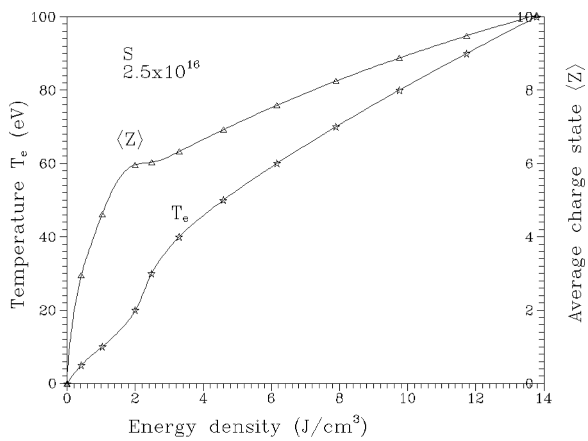

Fig. 4. Electron temperature and average charge dependencies. on specific energy

3. Computer results

We have presumed non-local thermodynamic "coronal" equilibrium. Default values of ionisation potentials (according to T.A. Carlson et al. [2]) for most part of our studied elements have been used. The missing data for the rest of elements, e.g. Sulphur, have been supplied according to C.E Moore [3]. The ionization fractions as functions of electron temperature have been calculated for plasmas created either by electric discharge in gas or vapours (Ar, S) or in the material ablated from the capillary wall (Polyacetal, Polyethylene, Teflon). Representative results are seen from the Figures 1, 3, 5 and 7 for Argon, Sulphur, Polyethylene and Teflon, respectively.

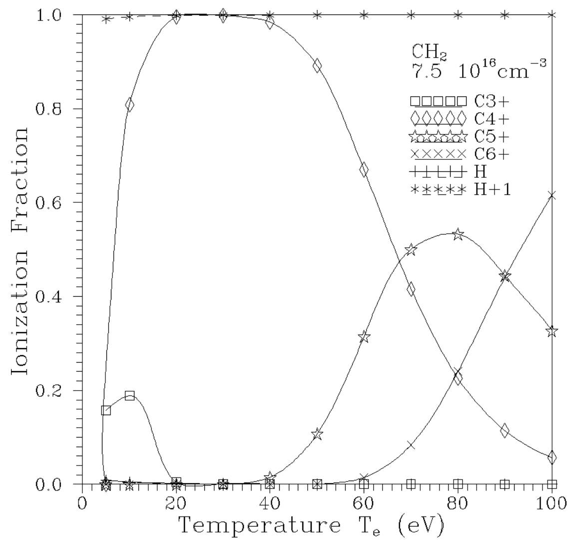

Fig. 5. Relative ionisation fractions of Carbon and Hydrogen ions. in Polyethylene plasma

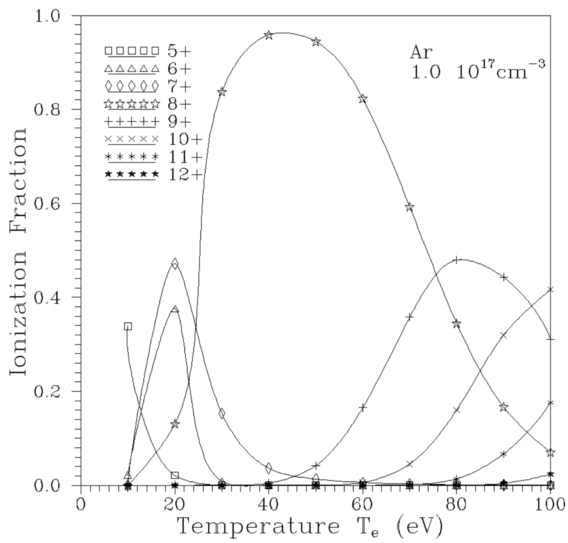

Fig. 7. Relative ionisation fractions of Carbon and Fluorine ions. in Teflon plasma

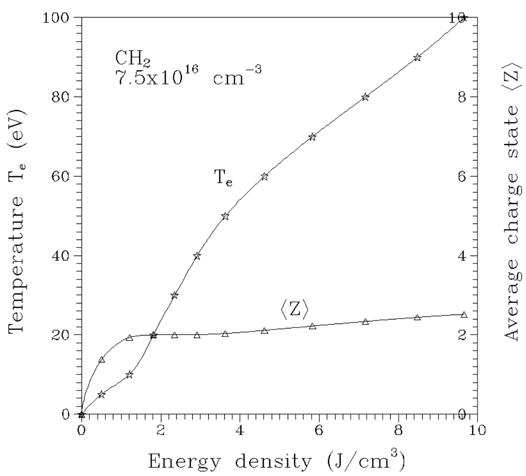

Fig. 6. Electron temperature and average charge dependencies. on specific energy

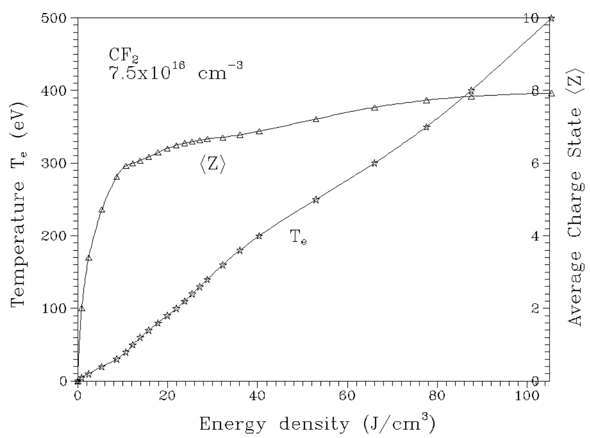

Fig. 8. Electron temperature and average charge dependencies. on specific energy

Dependencies of ionisation fractions on the electron temperature for a given atomic specimen are not remarkably influenced by a change of composition of a mixture. But, for a given electron temperature the thermodynamic properties of plasma like the specific energy are different for different mixtures.

Broad maxima of abundance of lasing Ne-like Ar^{8+} and S^{6+} ions are clearly seen from Fig. 1 and Fig. 3, resp. The optimum electron temperature is 30-60 eV for Argon and 20-30 eV for Sulphur. In the region of optimum temperatures the plasma energy density and the electron density $n_e =< Z > .n_{tot}$, , are remarkably higher for Argon than that for Sulphur, compare Fig. 2 and Fig. 4.

In the case of recombination pumping of H-like ions, prevailing amount of fully ionised atoms is required, the plasma electron temperature should be greater than 90 eV for Carbon, see Fig. 5 or Fig. 7, and greater than 300 eV for Fluorine, see Fig. 7. If the active medium for Carbon lasing is created via ablation of Polyethylene the specific plasma energy is half of that which is required when the ablation of Teflon is used (compare Fig. 6 and Fig. 8). The lasing effect with H-like Fluorine ion requires the plasma energy inload 3.5 times higher than that for the H-like Carbon in the same Teflon capillary.

The plasma resistivity calculated according to (2) is decreasing with decreasing energy density. For optimum electron temperatures in Argon, Sulphur, Polyethylene and Teflon plasma the resistivity has the values $4 \times 10^{-4}, 1 \times 10^{-3}, 1 \times 10^{-4}$ and $5 \times 10^{-5}\ \Omega.cm$, resp.

4. Conclusion

Optimum values of electron temperatures evaluated for Ne-like Ar^{8+} and S^{6+} ions are in very good correspondence to data published in [4, 5, 7]. The required energy density is remarkably smaller for Sulphur than for Argon.

Efficient pumping of H-like C^{5+} ion in recombination scheme requires initial electron temperature $T_e > 90\ eV$ which can be achieved by energy inload two times higher in Teflon than in Polyethylene plasmas.

H-like F^{8+} laser activity can be expected if the rapid cooling is started from initial $T_e > 300\ eV$. The energy density inload must be three times higher than for lasing C^{5+} in Teflon capillary.

Acknowledgements

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